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METALLOGRAPHIC STUDIES OF EROSION AND THERMO-CHEMICAL CRACKING OF CANNON TUBES

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The characteristic erosion features of fired cannons and the closely related surface alterations on laboratory simulation samples have been examined with a variety of electron optical and other analytical techniques. The results suggest that the heat-checking pattern is caused by the large differential thermal contraction between surface austenite and subsurface tempered martensite, the deep longitudinal cracks result from liquid-solid metal

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20. ABSTRACT

embrittlement primarily by copper, and the subsurface microstructural alterations are a consequence of intense carburization by the explosion gases. The observations could provide the basis for thermomechanical modeling of the erosion and cracking of cannon tubes.

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INTRODUCTION

The continuing studies at Benet Weapons Laboratory of the erosion of cannon tubes during firing have been described in keynote and contributed papers at Tri-Service Conferences and in the fracture mechanics and metallurgical literature.[1-4] The results of visual inspection and metallographic examination of the bore surfaces of fired cannon tubes have clearly established the occurrence of three rather distinct features, namely, (1) a corncob-like heat-checking pattern, (2) a series of deep cracks nearly aligned parallel to the tube axis, and (3) several etch resistant "white layers" and a region of "thermally altered ferrite" with microstructures and hardness values very different from the tempered martensite steel base. As mentioned in the forementioned papers and as discussed in detail in this report, these three erosion features appear to result from (a) thermal stresses, (b) fatigue crack propagation with the added influence of an embrittling agent, and (c) chemical reaction with the bore surface, namely, carburization.

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[1]Ahmad, I., "The Problem of Gun Barrel Erosion - An Overview," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, ARRADCOM, Dover, NJ, 29-31 March 1977, pp. I-1 - I-49, (Picard, J. P. and Ahmad, I., Eds.).

[2]Albright, A. A., Friar, G. S., and Morris, S. L., "Secondary Wear Characteristics and Effects in Ballistic Performance of the 105 mm M68 Gun," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, ARRADCOM, Dover, NJ, 29-31 March 1977, pp. II-178 - II-195, (Picard, J. P. and Ahmad, I., Eds.).

[3]Griffin, R. E., Pepe, J. and Morris, C., "Metallurgical Examination of Bore Surface Damage in a 5-Inch Gun," Metallography, Vol. 8, No. 6, December 1975, pp. 453-471.

[4]Davidson, T. E., Throop, J. F., and Underwood, J. H., "Failure of a 175 mm Cannon Tube and the Resolution of the Problem Using an Autofrettaged Design," Case Studies in Fracture Mechanics, AMMRC Conference Report 77-5, pp. 3.9.1 - 3.9.13, (Rich and Cartwright, Eds.).

Recently the optical metallographic studies have been augmented and extended by the application of a variety of electron beam instruments and other analytical equipment to develop a more detailed description of the major erosion features. Because of the very limited number of cannon tubes that are available, especially with a complete record of firing history, the program has also utilized simulation samples prepared in the laboratory by capacitance-discharge pulse heating.

EXPERIMENTAL MATERIALS METHODS

All samples examined were of 4340 steel and included sections cut from the breech area and bottom of the rifling of fired cannon tubes and from flat sheet tensile specimens heated by capacitance discharge as listed below.

Description of 4340 Steel Samples

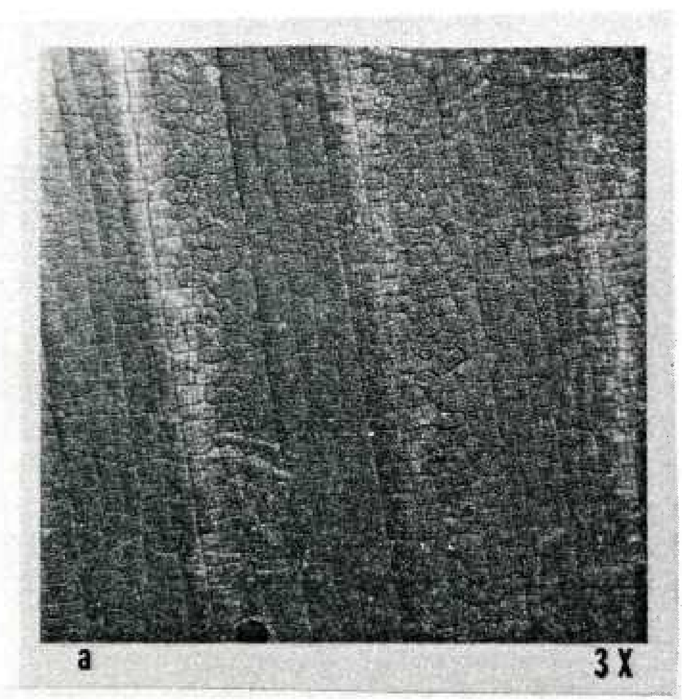
Cannon Tubes	- 6826
(105 mm)	- 7544 (Cr plated prior to firing)
	- T-45 (additive used)
Simulation Samples	- pulse heated in 3000 psi methane
	- Cu plated and pulse heated in vacuum

Selected samples were examined by optical microscopy, scanning (SEM), and high voltage transmission electron microscopy (HVEM) to study the surface and subsurface microstructures at high magnification and by energy dispersive x-ray spectroscopy (EDXS), Auger spectroscopy, Mossbauer spectroscopy, and secondary ion mass spectroscopy (SIMS) to determine the surface and near surface chemical composition.

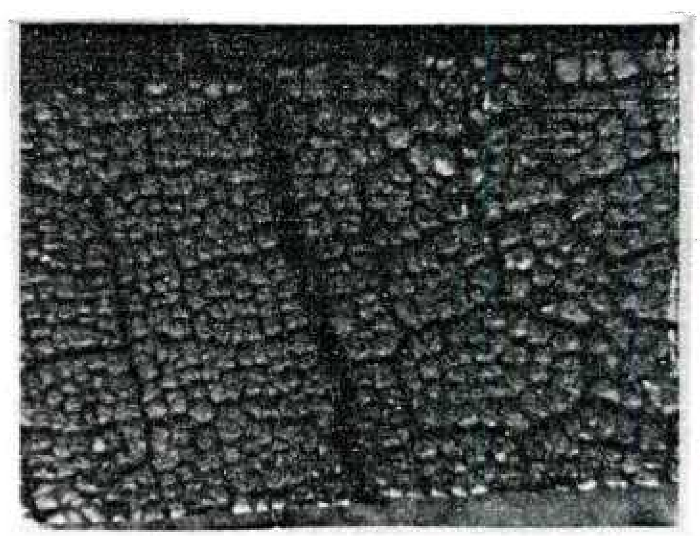
The results of the investigation are illustrated with representative examples obtained with the various samples examined and techniques employed.

EXPERIMENTAL RESULTS

The characteristic heat-checking pattern and deep cracks parallel to the rifling are illustrated in Figure 1. The bright areas are abrasion marks caused by the rotating Cu band. The appearance of this surface in the SEM is shown in Figure 2, along with an EDX spectrum illustrating the occurrence of a considerable amount of Ti and lesser concentrations of Al, S, K, and Cu. Point-to-point probing revealed that the Fe signal from the steel base largely came from the spaces between the hillocks and that the Cu was associated with the abrasion marks.

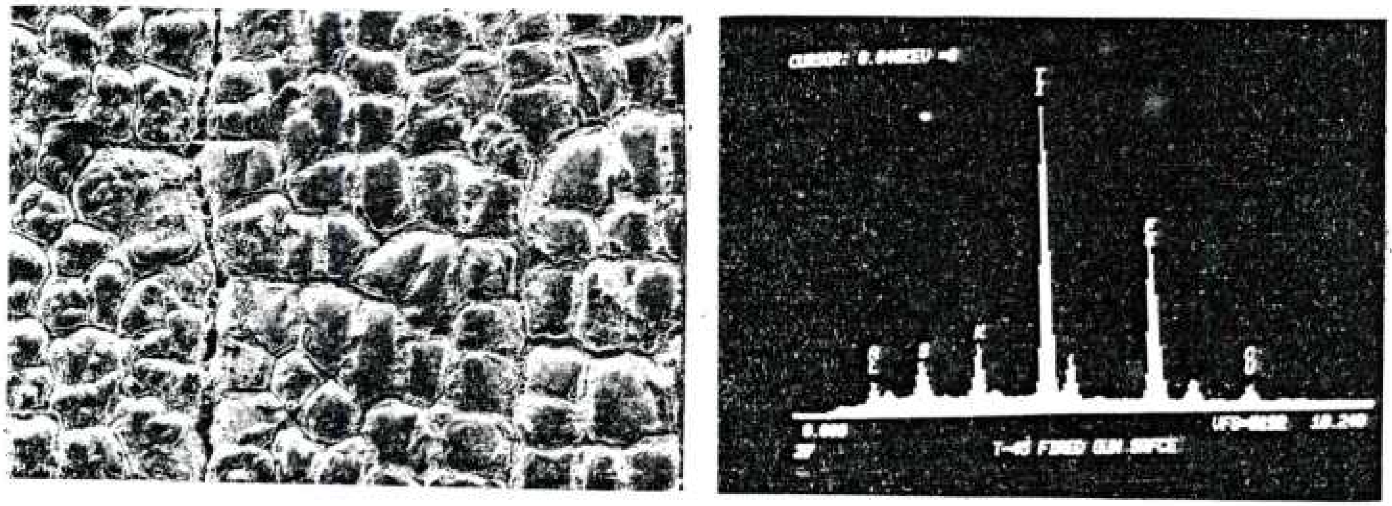


(a) (3X).



(b) (10X).

Figure 1. Cannon Tube T-45, Bore Surface.



(a) SEM (60X). (b) EDX.

Figure 2. Cannon Tube T-45, Bore Surface.

A Ni plated, polished, and lightly etched cross-section of sample T-45, illustrating the alternating pattern of shallow, deep, and very deep cracks that is typical of fired cannons, is shown in Figure 3.

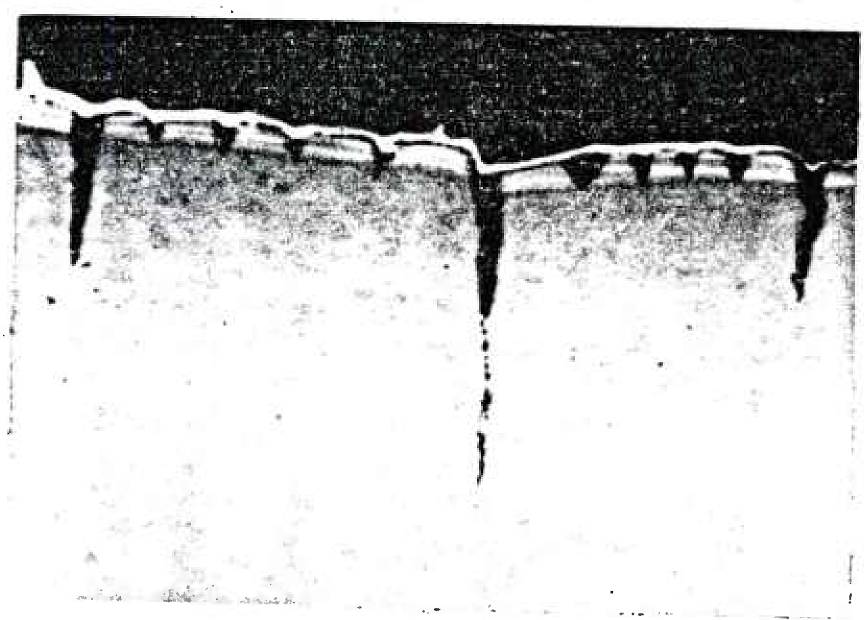
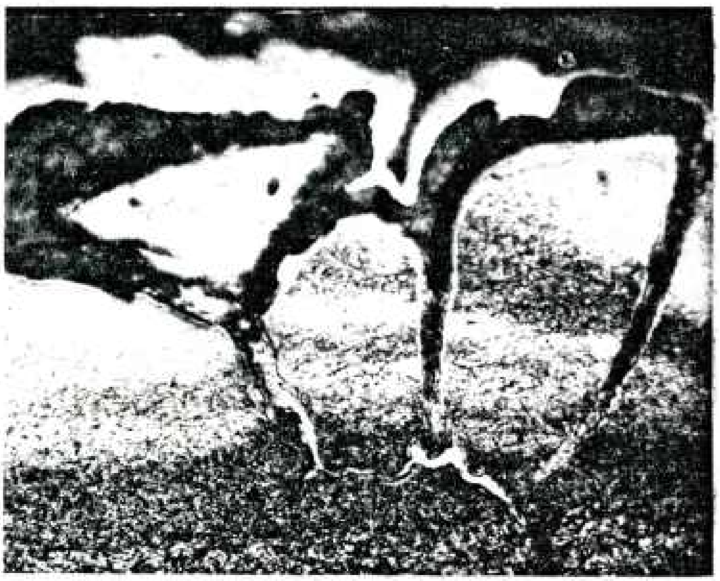
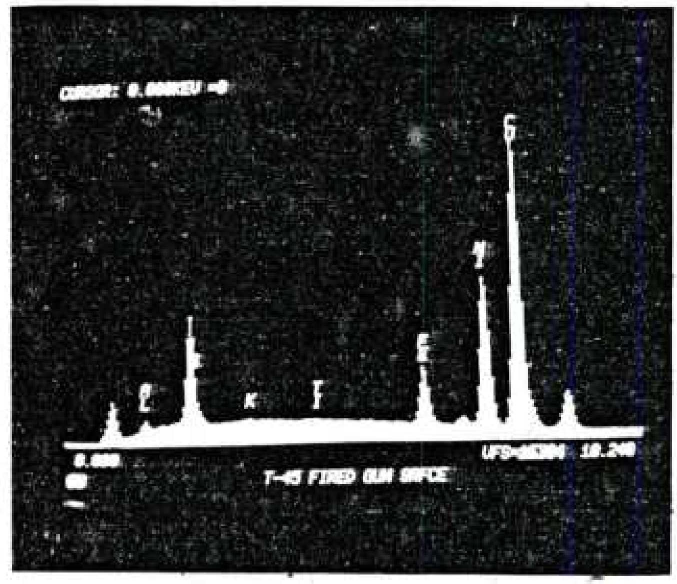


Figure 3. Cannon Tube T-45, Cross-Section. (50X)

The near-surface structure of this sample can be seen in more detail in the optical micrograph of a 15° taper section shown in Figure 4a. EDXS analysis of this same area in the SEM revealed that a considerable amount of Cu, and some S and Al were present in the altered ferrite region below the white layers. Penetration of Ni during plating demonstrated that these cracks were open to the bore surface.



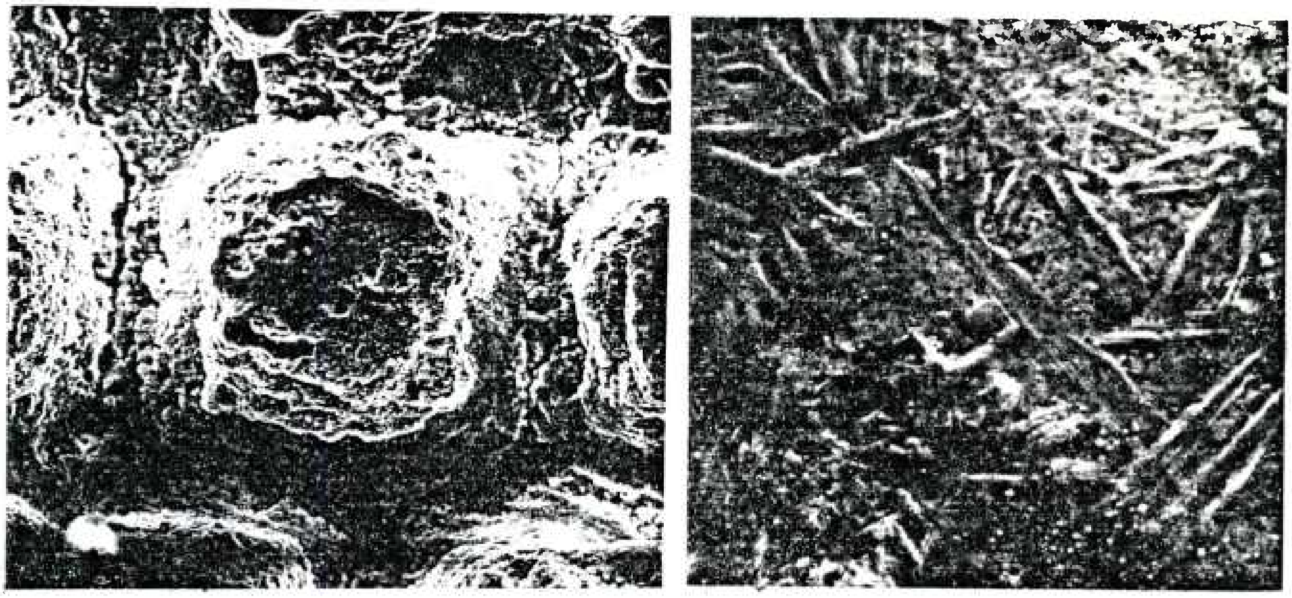
(a) Optical (200X).



(b) EDXS.

Figure 4. Cannon Tube T-45, Taper Sections.

Examination of the bore surface of cannon tube 6826 (no additive in the propellant) in the SEM revealed a rather different appearance, as illustrated in Figure 5. The small crystals visible on the surface at higher magnification were suspected to be cementite (Fe_3C). This opinion was confirmed by subsequent Auger, Mossbauer, and SIMS analyses of the surface, and by stripping the surface film and obtaining direct electron diffraction evidence for Fe_3C.



(a) (500X). (b) 2000X.

Figure 5. Cannon Tube 6326, Bore Surface.

The carbon concentration in the white layer region was determined by several techniques including a Mossbauer surface analysis method, depth profiling by Auger and SIMS, and profiles on cross-sections by electron probe analysis using a special light element detector. All of these methods indicated the presence of 0.25 to 0.5 μm of Fe_3C on the surface and a subsurface layer of about 2 to 10 μm of austenite containing two percent carbon near the surface and about one percent carbon in the interior. The very rough surface of eroded corrosion tubes precludes obtaining more than an estimate of the thicknesses of the white layer constituents by profiling. An example of a SIMS depth profile is illustrated in Figure 6.

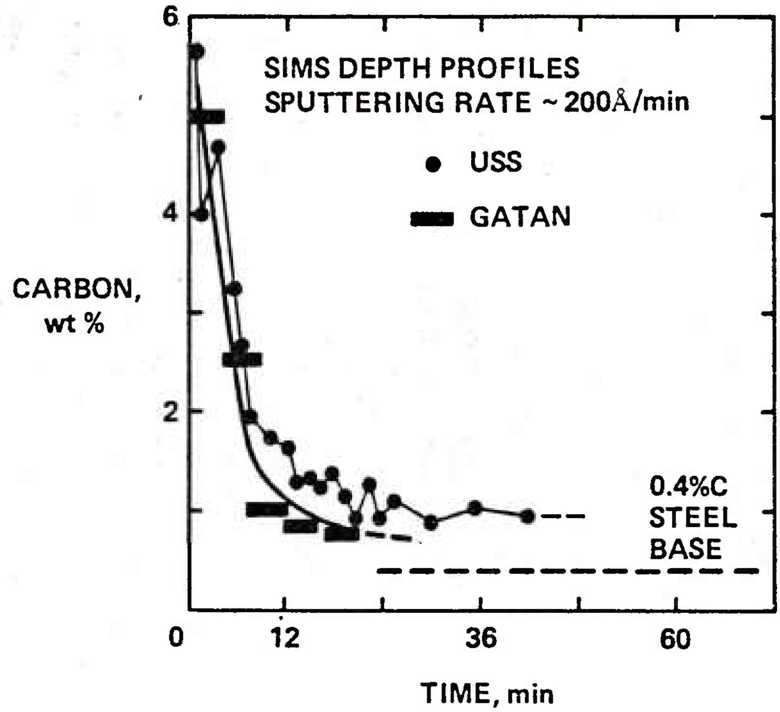
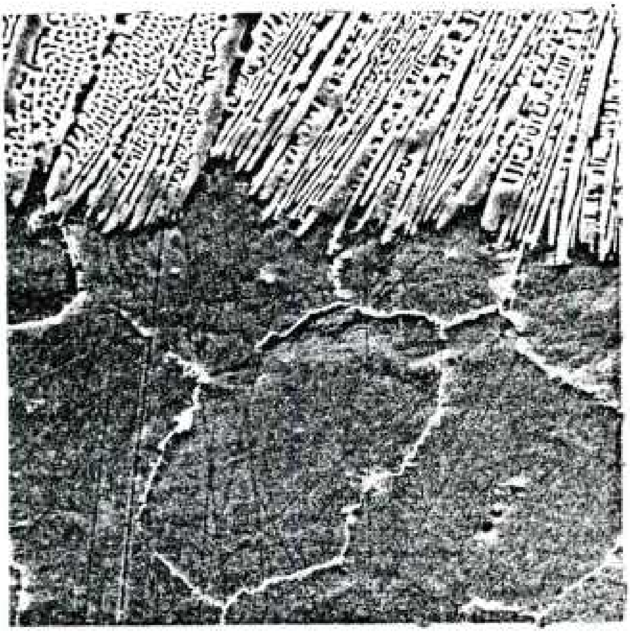


Figure 6. Cannon Tube 6826, Bore Surface.

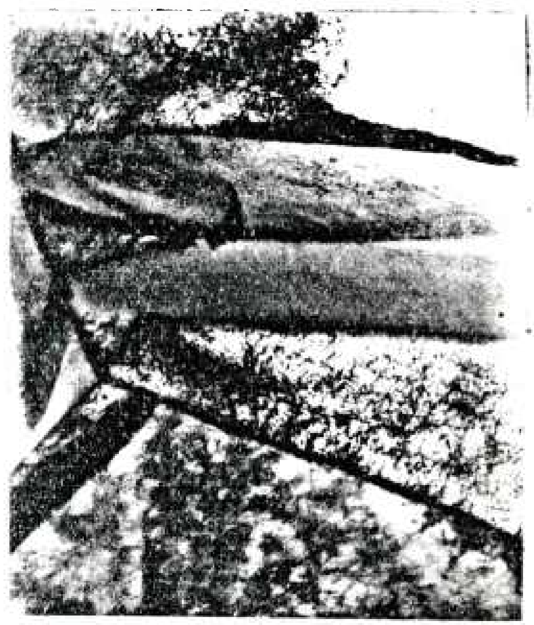
The effects of chemical alteration of the surface of 4340 steel during pulse heating in high pressure methane are illustrated in Figure 7. Polished and etched 6° taper sections reveal the appearance of the surface eutectic structure (with pools of austenite) and the grain boundary carbides in the subsurface austenite. The very fine scale of the eutectic suggests an extremely rapid solidification rate. An example of transformation of a surface austenite pool to martensite is illustrated in Figure 7a.

Transmission electron micrographs illustrating the lamellar structure of the surface carbide film and an example of the high carbon plate martensite which formed in the subsurface austenite region are shown in Figure 8. The electron diffraction pattern from this film confirmed that it was Fe_3C, i.e., identical to that observed for fired cannon specimens.



(a) SEM (2000X). (b) SEM (5000X).

Figure 7. Simulation Specimen Pulse Heated in Methane.

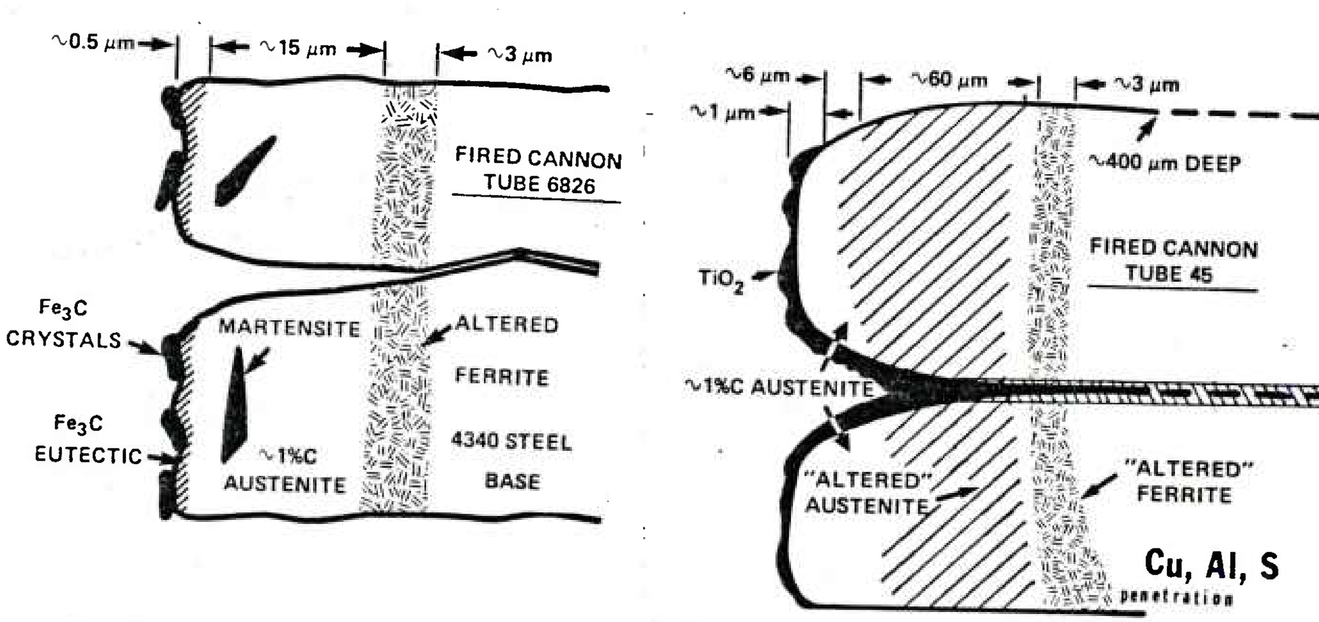


(a) HVEM (16,000X). (b) HVEM (21,500X).

Figure 8. Simulation Specimen Pulse Heated in Methane.

Although the white layer formed by pulse heating in methane is similar to that on fired cannons, some differences are to be expected. For example, the chemical activity of pure methane is probably greater than that of the explosion gases, and the cooling rate smaller than for a thick cannon tube.

The deep penetrating cracks in fired cannon tubes were found to contain Cu, and lesser amounts of Al and S right to the tip of the crack, i.e., more than 400 μm in some cases. The results of all of the various observations and analyses of eroded bore surfaces from two cannons are summarized schematically in Figure 9.



(a) (b)

Figure 9. Schematic Illustration of Cannon Bore Surface.

The observations of Cu penetration deep into the longitudinal cracks prompted some analogous experiments to pulse-heat specimens that had been Cu plated. An example of the cracks that developed at the root of the notch (used to localize the heating) is shown in Figure 10. The presence of Cu could be detected by EDXS in the cracks but penetration to their tips did not occur in any of the pulse-heated specimens.

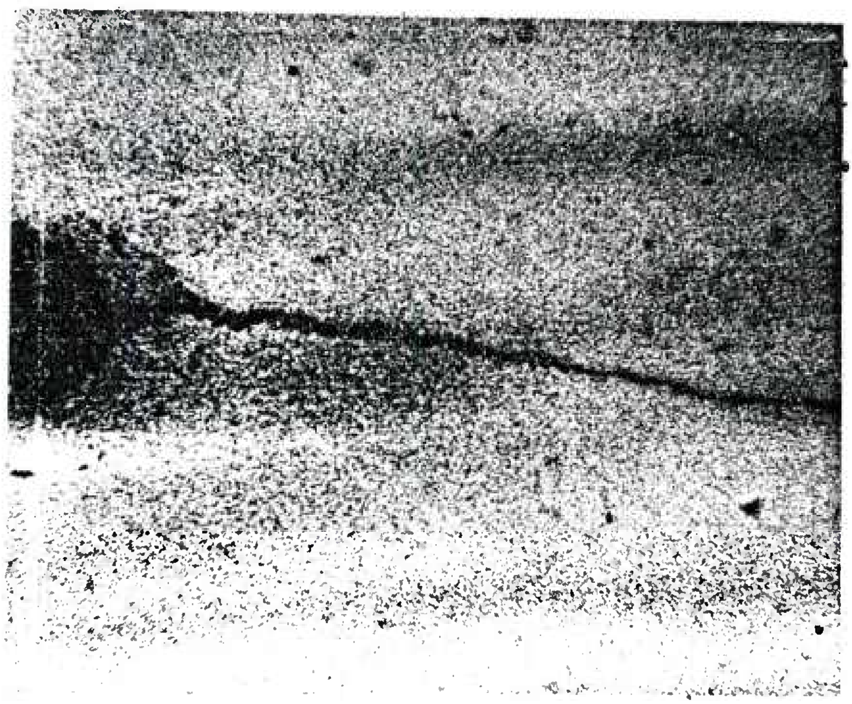


Figure 10. Notched, Cu Plated, and Pulse Heated 4340 Steel (50X).

SUMMARY OF OBSERVATIONS

The three major microstructural characteristics of eroded cannon barrels, mentioned in the Introduction of this report, are described below in order of their probable detrimental effects on the useful life of cannon barrels. General discussion of the factors that appear to determine erosion rate and suggestions for future work are presented in a separate section.

White Layer

The explosion gases are extremely carburizing to the extent that carbon-saturated liquid iron forms on the surface and solidifies rapidly after the firing cycle to form a thin layer of very fine eutectic of Fe_3C and Fe with a considerable amount of retained austenite. Carbon diffusion into the steel results in the formation and retention of a layer of relatively soft austenite and an altered ferrite region hardened by the precipitation of alloy carbides. No white layer forms on surfaces protected by chrome plating.

Heat Checking

Rupture of the surface results from rapid thermal expansion and contraction of the surface during each firing cycle. The expansion coefficients of ferrite and austenites are very different so that the presence of a surface layer of high carbon austenite (with a very low M_s) can result in very large tensile strains, as illustrated qualitatively in Figure 11. Because of the large mass of the cannon tube, cooling of the heat-affected zone is relatively rapid and the effective strain rate fairly high, resulting in the formation of "quenching cracks". The occurrence of coarse and fine networks suggests that the stresses relieved by an initial stage of crack formation build up during further cooling and cause secondary cracking. This is analogous to the familiar paint cracking or mud flat crack patterns.

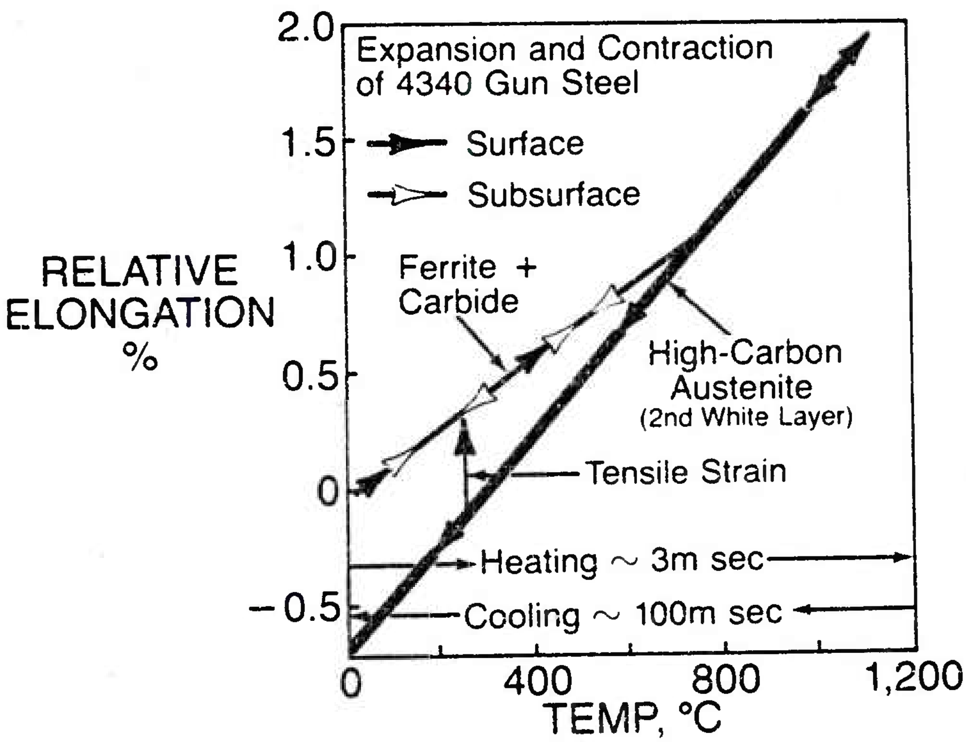


Figure 11. Illustration of Origin of Heat Checking.

Longitudinal "Fatigue" Cracks

Sharp cracks, 0.2 to 1 mm deep, form parallel to the rifling with a spacing of about 1 mm (the very deep cracks are spaced about 10 mm apart). These cracks are associated with regions of Cu transfer from the rotating band. The cracks contain easily detectable Cu, some S (presumably from the propellant), and Al (which may be a contaminant from metallographic polishing), to very near the crack tips. Propagation of the deep cracks during each firing cycle is presumably enhanced by the embrittling agents (Cu, S, Al) which may be forced into the cracks by the explosion pressure.

DISCUSSION

The general results of this study largely confirm the observations of previous investigators and support many of their conjectures, while the new, or in some cases more quantitative information, provides the basis for a more detailed understanding of cannon barrel erosion and cracking.

Several metal removal mechanisms must be involved in the erosion and wear of cannon barrels. The average wear rate is about 25 μm per round unless an additive is used in the propellant. This is comparable to the depth of the crevices between the "kernals" of the heat-check pattern so that it is reasonable to presume that they are removed largely during each firing cycle. This could occur if the proturberances are converted to liquid metal and swept away by the explosion. The reduced erosion resulting from lower firing temperatures, the application of Cr plating or use of TiO_2 additive in the propellant support this view.

The heat-checking cracks expose the subsurface of the bore to the carburizing atmosphere and enhance formation of white layers. In addition, on occasion, some cracks link up below the surface causing the formation of large pits when the metal "plug" is forced out leading to accelerated erosion. The fatigue cracks due to Cu embrittlement may also increase subsurface carburization.

Further laboratory studies are performed to determine the effects of peak pulse heating temperature on carbon pickup, and the reduction afforded by the use of protective metal coatings. A model is under consideration for the mechanism of the formation of heat checking. These and other studies of the effects of gas pressure, temperature on gun steel, and on gun steel protected

by chromium and tantalum coating are being undertaken and will be reported in a later publication.

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1. Ahmad, I., "The Problem of Gun Barrel Erosion - An Overview," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, ARRADCOM, Dover, NJ, 29-31 March 1977, pp. I-1 - I-49, (Picard, J. P. and Ahmad, I., Eds.).

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